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# Effect of the Volume Rate of Application on the Glasshouse Performance of Crop Protection Agent/Adjuvant Combinations

B. Terence Grayson,* Paul J. Price & David Walter

Shell Research Limited, Sittingbourne Research Centre, Sittingbourne, Kent ME9 8AG, UK

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**Abstract:** The effects of volume rate of application on the glasshouse performance of three recently developed crop protection agent/adjuvant combinations are discussed. High volume rates of application on easy-to-wet foliage, such as potato (*Solanum tuberosum*, L.) caused reduction of the adjuvant-enhanced performance of dimethomorph seen at low volume rates. These reductions were largely attributable to relatively lower spray retention with spray drop coalescence and run-off being observed, particularly at the higher adjuvant rates. On difficult-to-wet foliage (wheat, *Triticum aestivum*, L.; oat, *Avena sativa*, L.) two different effects were seen. With a metconazole formulation/'Dobanol' 91-6 combination on wheat, no systematic changes in performance were observed with change in volume rate. With a flamprop-M-isopropyl formulation/'Dobanol' 25-7 combination, statistically significant increases in performance were seen with increasing volume rate. In both cases the observations can be explained as the result of a combination of interacting factors involving spray pattern, spray deposition and, by inference, foliar uptake of the crop protection agent, the proportions of which differed between the two cases. It is suggested that the effect of volume rate of application on performance of adjuvant-containing formulations is investigated on easy-to-wet foliage to determine the upper limits and on difficult-to-wet foliage to determine any variation in performance that may occur. Such information will guide the design of field trials and may aid interpretation of field results.

Key words: fungicide, herbicide, dimethomorph, metconazole, flamprop-M-isopropyl, potato, wheat, oat, late blight, powdery mildew, adjuvants, alcohol ethoxylates, formulation, application

## 1 INTRODUCTION

Emulsifiable oils and, in particular, surfactant adjuvants have been shown to give significant enhancements in the performance of the normal formulations (emulsifiable concentrates, ECs; suspension concentrates, SCs; wettable powders, WPs) of several crop protection agents (CPA) applied as foliar treatments in recent glasshouse studies.[1–3] A number of these glasshouse observations have been confirmed in field testing.[4,5]

* To whom correspondence should be addressed at: Department of Biological Sciences, University of Portsmouth, King Henry I Street, Portsmouth PO1 2DY, UK.

A frequent purpose of foliar applications of CPA, especially with the use of adjuvants to promote uptake (penetration), is to cause diffusion of the CPA through the leaf cuticle to the points of biological action in epidermal and mesophyll cells within leaves or, after systemic movement, at remote points within plants. Since any rate of diffusion across an interface is directly related to concentration difference (Fick's Law),[6] the rate of diffusion of a CPA across a leaf cuticle will be determined both by its concentration in the applied spray solution and, in the presence of an adjuvant which will also diffuse through the leaf cuticle,[7–9] by the concentration of the adjuvant.

Furthermore, since many of the most successful adjuvants are surfactants, their concentrations will affect the

behaviour both of spray *deposition* (i.e. that originally captured by the leaf surface) on difficult-to-wet leaf surfaces[10–13] and of spray *retention* (i.e. that remaining on the leaf surface until the spray deposits have dried).[14,15] This latter point could be particularly important at higher volume rates of application when the volume of spray solution retained on a leaf is near its saturation capacity and spray solution run-off could be exacerbated by the presence of a surfactant. If differences in either deposition or run-off occurred between different volume rates of application then, of course, different amounts of CPA would be available for foliar uptake and biological performance. Thus at least three factors that will have direct consequences on performance may be affected through changing the volume rate of application of solutions which contain surfactants. For a thorough understanding of this potential variable and for the successful transfer of adjuvant-enhanced performance seen in glasshouse trials (where volume rates of application are generally constant and relatively low, 250–400 litre ha$^{-1}$) to field trials, it is necessary to evaluate this variable. This will provide information that will not only guide recommendations for optimal volume rates of application in the field, but also provide a measure of sensitivity of performance to application volume rates where adherence to recommended volume rates may be less exact. This study assessed the effects of volume rate of application on the performance of three CPA adjuvant combinations, involving dimethomorph (I), metconazole (II) and flamprop-M-isopropyl (III), that have been reported recently.[1–5]

## 2 EXPERIMENTAL

### 2.1 Materials

Formulations of pesticides were prepared to the compositions given in Table 1 by the Formulation Department at Sittingbourne Research Centre. 'Dobanol' 91-6 ($C_9$–$C_{11}$ alcohol ethoxylate with six moles of ethylene oxide) and 'Dobanol' 25-7 ($C_{12}$–$C_{15}$ alcohol ethoxylate with seven moles of ethylene oxide) were obtained from Shell Chemicals UK Ltd, Carrington, UK.

**TABLE 1**
Composition of Pesticide Formulations Used

| | *Composition (g)* | | |
|---|---|---|---|
| | *WPI* | *DCII* | *ECIII* |
| Dimethomorph | 500 | — | — |
| Metconazole | — | 100 | — |
| Flamprop-M-isopropyl | — | — | 200 |
| Mixed emulsifiers | — | 80 | 60 |
| Mixed solvents | — | to 1 litre | |
| Wetting agent | 20 | — | — |
| Suspending agent | 80 | — | — |
| Mineral filler | 400 | — | — |

### 2.2 Plant propagation and treatment prior to spraying

Potatoes (*Solanum tuberosum*, L. cv. Desiree) were propagated from tuber cuttings and grown to the five- to six-leaf stage under growth-room conditions (temperature, 10°C; lighting, 12 h photoperiod under lamps of 125 W cool white fluorescent tubes giving 155 μmol m$^{-2}$ s$^{-1}$ in the PAR, 400–700 nm). The apices and any side shoots were removed to leave plants with three well-developed leaves. These leaves were inoculated by spraying the adaxial surface with a freshly prepared suspension of spores of late blight (*Phytophthora infestans* de Bary, ~15 000 sporangia ml$^{-1}$) obtained from potato hosts. The inoculated plants were transferred to a high humidity chamber (17°C) for 20 h before being removed and the leaves allowed to dry (1–2 h) before spraying.

Wheat plants (*Triticum aestivum*, L. cv. Hornet) were grown to growth stage 11 (Zadoks scale) under normal glasshouse propagation conditions (temperature, 20–25°C; lighting, 16 h photoperiod of daylight supplemented by metal halide/sodium lamps giving ~200 μmol m$^{-2}$ s$^{-1}$ in the PAR). They were inoculated with powdery mildew (*Erysiphe graminis*, DC.f. sp. tritici *Marchol*) one day before spraying using dry inoculum from diseased plants.

Cultivated oats (*Avena sativa*, L. cv. Oberon) were grown to the first leaf stage (growth stage 11, Zadoks scale) under normal glasshouse propagation conditions (temperature, 20–25°C; lighting, 16 h photoperiod of daylight supplemented by metal halide/sodium lamps giving ~200 μmol m$^{-2}$ s$^{-1}$ in the PAR). Any partially emerged plants were removed before spraying.

### 2.3 Preparation of spray solutions and application

#### 2.3.1 *Dimethomorph/potatoes*

Amounts (0·05, 0·1, 0·2, 0·4 g) of WPI were dispersed in different volumes (200, 400, 600 ml) of tap water to give three series of suspensions. Amounts (1·0, 3·0 g) of 'Dobanol' 25-7 were also dissolved in different volumes (200, 400, 600 ml) of tap water to give a further three series of solutions. An aliquot (20 ml) of each dimethomorph suspension was mixed with an equal aliquot of either water or 'Dobanol' 25-7 solution from the corresponding series. Each of the resulting dispersions was sprayed onto four inoculated potato plants at a volume rate (200, 400, 600 litre ha$^{-1}$) appropriate to each series of dispersions using a moving belt track sprayer, with the speed adjusted and calibrated to give the desired volume rate of application, and equipped with a static hydraulic flat fan 8002E nozzle (Spraying Systems Co.,

Illinois) operating at 276 kPa, as described previously.[12] At each volume rate the applications were equivalent to 12·5, 25, 50, 110 g ha$^{-1}$ of dimethomorph and 0, 500 1500 g ha$^{-1}$ of 'Dobanol' 25-7. A further four inoculated plants were sprayed with water at each volume rate to act as untreated controls. After being sprayed, all plants were taken automatically into a drying tunnel, through which an airstream at ambient temperature was passed, and left until the spray deposits were dry (15–20 min).

A similar but reduced matrix of solutions (see Table 3) was also prepared containing 932 mg litre$^{-1}$ gentian violet and sprayed onto five potato plants and three watchglasses (10 cm diameter), placed on pots amongst the plants, at the appropriate volume rates (200, 400, 600 litre ha$^{-1}$).

### 2.3.2 *Metconazole/wheat plants*

Aliquots (0·13, 0·25, 0·5, 1·0 ml) of DCII were dispersed in different volumes (150, 300, 500 ml) of tap water to form three series of dispersions. Amounts (0·25, 1·0 g) of 'Dobanol' 91-6 were also dissolved in different volumes (150, 300, 500 ml) of tap water to form a further three series of solutions. An aliquot (20 ml) of each formulation dispersion from each series was mixed with an equal volume of either water or 'Dobanol' 91-6 solution from the corresponding series. Each solution mixture was sprayed onto triplicate pots of inoculated wheat plants at volume rates (150, 300, 500 litre ha$^{-1}$) appropriate to each series of solutions using a track sprayer equipped with a hydraulic flat fan 80015 nozzle (Spraying Systems Co., Illinois) operating at 117 kPa. This pressure was selected so as to be able to achieve the low application rates at the highest speed of operation of the track sprayer and, although below normal commercial practice under field conditions, it is still within the nozzle manufacturer's limits. At each volume rate the applications were equivalent to 6·3, 12·5, 25, 50 g ha$^{-1}$ metconazole and 0, 125, 500 g ha$^{-1}$ 'Dobanol' 91-6.

A similar but reduced matrix of solutions (see Table 5) was also prepared containing 950 mg litre$^{-1}$ gentian violet and sprayed onto four pots of wheat plants and two watchglasses (10 cm diameter), placed on pots amongst the plants, at the appropriate volume rate (150, 300, 500 litre ha$^{-1}$).

### 2.3.3 *Flamprop-M-isopropyl/oat plants*

Aliquots (0·37, 0·75, 1·5, 3·0, 6·0 ml) of ECIII were dispersed in different volumes (150, 300, 500 ml) of tap water to form three series of dispersions. Amounts (0·5, 3·0 g) of 'Dobanol' 25-7 were also dissolved in different volumes (150, 300, 500 ml) of tap water to form a further three series of solutions. An aliquot (20 ml) of each formulation dispersion from each series was mixed with an equal volume of either water or 'Dobanol' 25-7 solution from the corresponding series. Each solution mixture was sprayed onto triplicate pots of oat plants at volume rates and under the operating conditions as given for metconazole/wheat. At each volume rate the applications were equivalent to 38, 75, 150, 300, 600 g ha$^{-1}$ flamprop-M-isopropyl and 0, 250, 1500 g ha$^{-1}$ 'Dobanol' 25-7. A further three pots of oat plants were also sprayed with water at each volume rate to act as untreated controls.

A similar but reduced matrix of solutions (see Table 8) was also prepared containing 840 mg litre$^{-1}$ gentian violet and sprayed onto seven pots of oat plants and two watchglasses (10 cm diameter), placed on pots amongst the plants, at the appropriate volume rate.

## 2.4 Plant treatment and biological assessment

In all cases plants sprayed with solutions containing no dye were returned either to the glasshouse (oat, wheat), or growth room (potato; temperature, 17°C; lighting, 16 h photoperiod under sodium lamps (250 W, Sont GEC solarcolor) giving 155 $\mu$mole m$^{-2}$ s$^{-1}$ in the PAR 400–700 nm; relative humidity, ~70%). In all cases the plants were watered by sub-irrigation only and assessed for biological effect after a suitable interval as indicated for each treatment/plant combination:

*dimethomorph/potatoes:* visual assessment of percentage area of sporulating infection after three days under growth room conditions and a further day, incorporating a dark period of 8 h, under high humidity conditions;

*metconazole/wheat:* visual assessment on a linear 0–9 scale (0 = no disease, 9 = complete cover) of sporulating disease on inoculated foliage eight days after spraying;

*flamprop-M-isopropyl/oats:* measurement of the length of the second leaf of each plant from the ligule to its tip eight days after spraying, including control plants sprayed only with water.

## 2.5 Measurement of spray deposition

The leaves from each plant (potato) or pot of plants (oat, wheat) sprayed with gentian violet solutions were harvested after the spray deposits had dried and the fresh weight of each replicate recorded. Each replicate was washed with acetone + water [1 + 1 by volume; 10 ml (potato, wheat) or 3 ml (oat); 2–3 min] to recover the gentian violet and its concentration in each solution measured by absorbance at 588 nm using a set of standard solutions of gentian violet (1–10 $\mu$g ml$^{-1}$) in the same solvent to calibrate the spectrophotometer (Unicam SP8/400). Previous studies have shown that this procedure gave quantitative recoveries of gentian

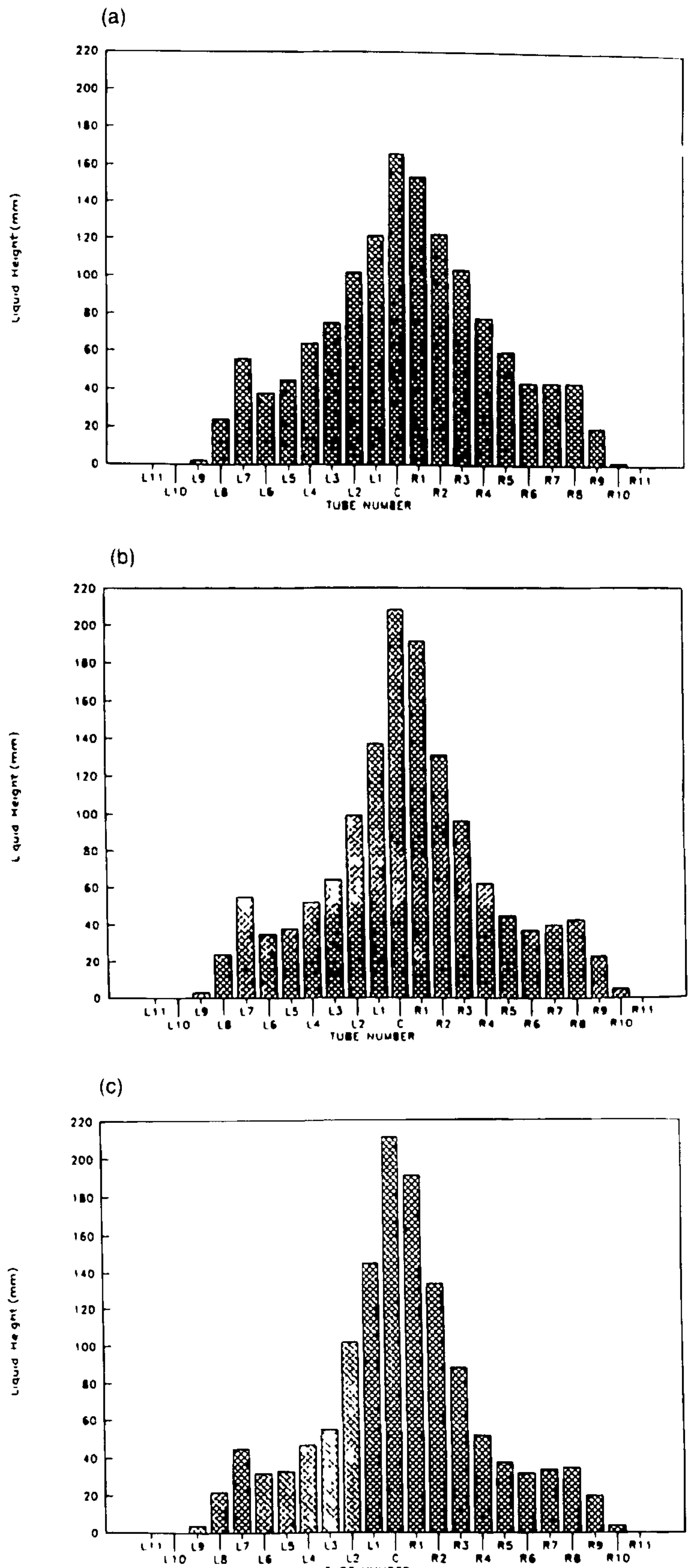


**Fig. 1.** **Spray pattern,** 80015 nozzle at 117 kPa. (a) Water, (b) 'Dobanol' 91-6 at 125 g $ha^{-1}$, (c) 'Dobanol' 91-6 at 500 g $ha^{-1}$.

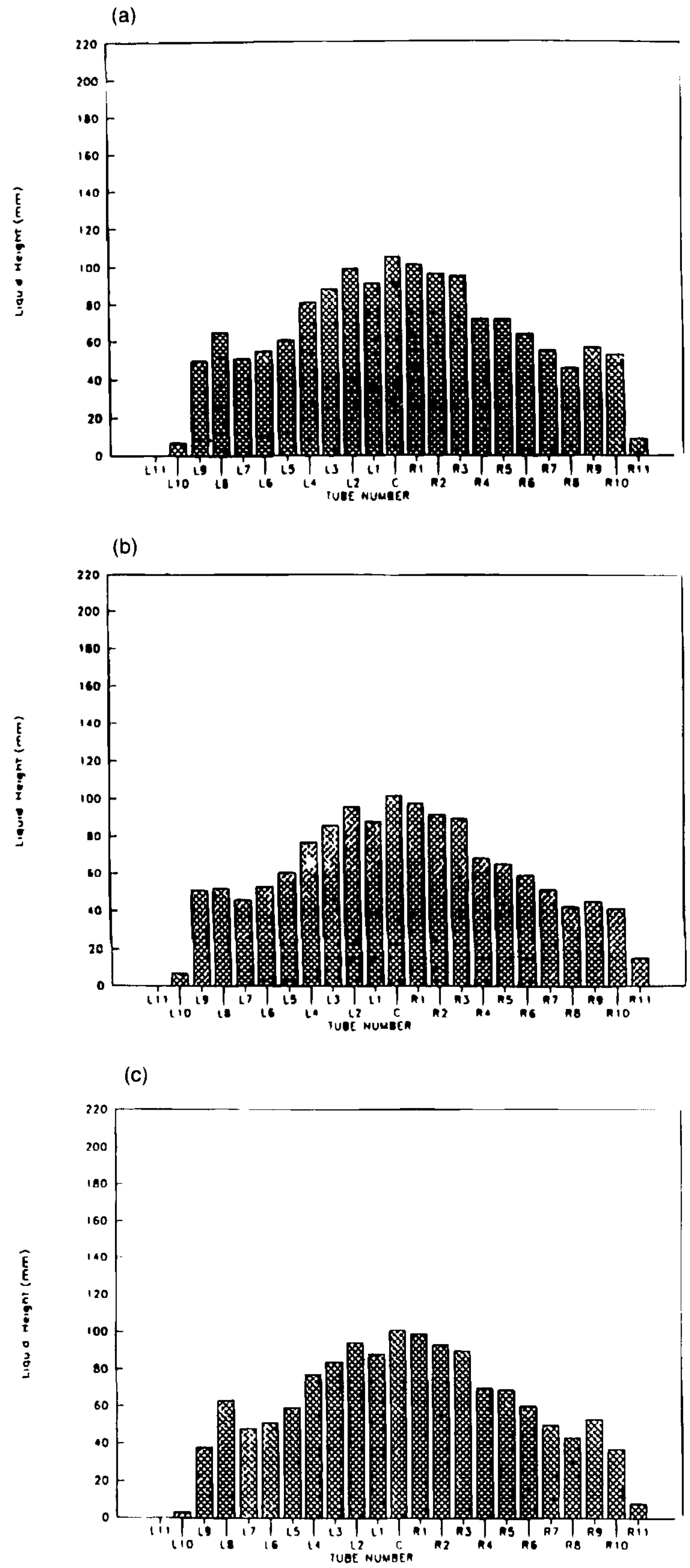


**Fig. 2.** Spray pattern, 80015 nozzle at 117 kPa. (a) DCII at 50 g ha$^{-1}$, (b) DCII at 50 g ha$^{-1}$ + 'Dobanol' 91-6 at 125 g ha$^{-1}$, (c) DCII at 50 g ha$^{-1}$ + 'Dobanol' 91-6 at 500 g ha$^{-1}$.

violet.[16] The surface area of the harvested foliage was calculated knowing its weight and the weight/surface area correlation obtained by measuring the surface areas (Detta T surface area meter) of known weights of foliage taken from the same batch of plants. The spray deposition per unit area ($\mu l\ cm^{-2}$) was calculated knowing the concentration of gentian violet in the wash solution, its volume, the foliage surface area and the concentration of gentian violet in the original spray solution.

### 2.6 Measurement of the spray swath profile

A patternator was fitted with the same hydraulic pressure nozzle (80015, Spraying Systems Co., Illinois) used for the metconazole and flamprop-M-isopropyl sprays detailed above. A volume (1 litre) of water and a series of DCII/'Dobanol' 91-6 spray solutions (see Figs 1, 2) were sprayed onto the patternator table equipped with collecting troughs at 5 cm intervals through the nozzle at the same pressure (117 kPa) used to spray the cereal plants. The volumes collected in each trough were noted and plotted as histograms (Figs 1, 2).

### 2.7 Statistical analyses

The data for the biological assays were subjected to analyses using a logistic dose response model PROC NLIN from the statistical package SAS[17] on an IBM 3090 computer, to give estimates of 90% control ($ED_{90}$ values) and associated fiducial limits.

## 3 RESULTS AND DISCUSSION

In order to achieve the aims of this study it was essential to keep the spray operating conditions constant during the application for each plant/CPA/adjuvant combination so that any trends in performance could be attributed only to variation in the volume rate of application. Therefore, for each situation, the nozzle type and operating pressure were kept constant and the different volume rates of application were obtained by varying only the speed at which the plants passed beneath the nozzle.

### 3.1 Dimethomorph/potatoes, late blight

Application of the dimethomorph WPI formulation onto potatoes inoculated with late blight gave little therapeutic control of the disease with applications up to 100 g AI $ha^{-1}$ (Table 2), in complete agreement with previous studies.[1] Furthermore, increase of volume rates of application up to 600 litre $ha^{-1}$ had no effect on this total lack of performance (Table 1).

Addition of 'Dobanol' 25-7 to dispersions of WPI brought about a significant change in the ability of WPI to give therapeutic control of one-day-old infections of late blight, increasing with increase of the adjuvant application rate up to 1500 g $ha^{-1}$, again in confirmation of previous results.[1]

However, increase of the volume rate of application from 200 litre $ha^{-1}$ to 400 and 600 litre $ha^{-1}$ caused a systematic and significant decrease in performance of these dimethomorph/'Dobanol' 25-7 combinations, with the decreases being more obvious with the weaker, 500 g $ha^{-1}$ 'Dobanol' 25-7, treatments (Table 2).

Explanation for these variations can be found from examination of the amounts of spray retained on the foliage for some of the WPI/'Dobanol' 25-7 combinations (Table 3). In this study the amounts of spray deposited onto watchglasses placed on pots amongst the potato plants was also measured. It can be seen that, at 200 litre $ha^{-1}$, the amount deposited (overall mean = $1{\cdot}9\ \mu l\ cm^{-2}$) was close to the nominal value ($2{\cdot}0\ \mu l\ cm^{-2}$), but that at higher volume rates (400 and 600 litre $ha^{-1}$) the amounts found ($3{\cdot}6$ and $5{\cdot}3\ \mu l\ cm^{-2}$) were below their nominal values ($4{\cdot}0$ and $6{\cdot}0\ \mu l\ cm^{-2}$). However, of more importance was the observation that spray retention onto potato leaves tended to decrease with increase of 'Dobanol' 25-7, even at 200 litre $ha^{-1}$. Without the additive spray retention ($1{\cdot}8\ \mu l\ cm^{-2}$) was close to that found on watchglasses, but retention fell to 79% and 71% of that on watchglasses with 500 and 1500 g $ha^{-1}$ 'Dobanol' 25-7 respectively.

At 400 litre $ha^{-1}$, the amounts of spray retained from application of WPI alone onto potato leaves was only 72% of that on watchglasses, and at 600 litre $ha^{-1}$ this proportion fell to an even lower value of 57%. Addition of 'Dobanol' 25-7 to these spray solutions exacerbated this situation in a systematic manner, such that at 600 litre $ha^{-1}$ with 1500 g $ha^{-1}$ of 'Dobanol' 25-7 only 50% of the spray deposited on watchglasses was retained on potato leaves. There was no effect of the WPI concentration, up to the maximum application rate of 100 g $ha^{-1}$ used in these studies, on spray retention on either watchglasses or potato leaves. This is in accord with other data[19] that the concentrations of surfactants in spray dilutions of 500 g $kg^{-1}$ WP formulations are generally so low that they cause only very small reductions in surface tensions of spray solutions and do little to facilitate spray drop coalescence and run-off.

The conclusion is that spray retention of WPI, and hence its fungicidal performance, on the easily wet foliage of potatoes can readily be reduced from that expected by an increase in the volume rate of application, especially in the presence of a surface-tension-reducing agent such as 'Dobanol' 25-7 which otherwise acts as a highly effective performance-enhancing adjuvant.

**TABLE 2**
Effect of Volume Rate of Application on the Performance of WPI/'Dobanol' 25-7 Combinations in the Therapeutic Control of Late Blight on Potatoes

| *Nominal application volume rate (litre ha⁻¹)* | *Dobanol 25-7 application rate (g ha⁻¹)* | *Leaf area infected*[a] (%) *WPI Application rate (g AI ha⁻¹)* 12·5 | 25 | 50 | 100 | $ED_{90}$ (g AI ha⁻¹) *Calculated value*[b] | *95% Confidence limits* |
|---|---|---|---|---|---|---|---|
| 200 | 0 | 78 | 75 | 62 | 69 | 1737a | 668<br>4516 |
| | 500 | 39 | 14 | 9 | 5 | 39bc | 19<br>84 |
| | 1500 | 8 | 5 | 5 | 1 | 9d | 6<br>13 |
| 400 | 0 | 57 | 47 | 69 | 61 | 2302a | 603<br>8792 |
| | 500 | 30 | 29 | 13 | 26 | 95b | 56<br>161 |
| | 1500 | 14 | 12 | 5 | 2 | 16cd | 9<br>29 |
| 600 | 0 | 83 | 71 | 65 | 60 | 2110a | 904<br>4924 |
| | 500 | 26 | 61 | 51 | 34 | 738a | 365<br>1494 |
| | 1500 | 24 | 12 | 7 | 4 | 33c | 24<br>46 |

[a] Infection on leaves sprayed only with water = 83%.
[b] $ED_{90}$ values with the same letter are not significantly different at a 95% confidence level.

**TABLE 3**
Effects of Spray Volume Rate and WPI and 'Dobanol' 25-7 Application Rates on Spray Deposition onto Watchglasses and Potato Leaves

| *Nominal application volume rate (litre ha⁻¹)* | *'Dobanol' 25-7 application rate (g ha⁻¹)* | *Deposition (μl cm⁻²)* *Watchglass*[a] *WPI application rate (g AI ha⁻¹)* 0 | 100 | *Potato leaf*[b] 0 | 100 | *Deposition Leaf/watchglass* (%) |
|---|---|---|---|---|---|---|
| 200 | 0 | 1·9 | 1·9 | 1·8 | 1·8 | 94 |
| | 500 | 1·8 | 1·8 | 1·3 | 1·5 | 79 |
| | 1500 | 2·0 | 1·9 | 1·4 | 1·4 | 71 |
| 400 | 0 | 3·7 | 3·4 | 2·7 | 2·4 | 72 |
| | 500 | 3·8 | 3·5 | 2·0 | 2·2 | 58 |
| | 1500 | 3·5 | 3·5 | 1·8 | 1·8 | 52 |
| 600 | 0 | 5·4 | 5·3 | 2·9 | 3·2 | 57 |
| | 500 | 5·0 | 5·2 | 2·7 | 2·9 | 55 |
| | 1500 | 5·6 | 5·0 | 2·5 | 2·8 | 50 |

[a] Mean of three replicates.
[b] Mean of five replicates.

In field trials of this type of dimethomorph formulation to easily wet leaf surfaces, particularly in the presence of performance-enhancing surfactant adjuvants, it is recommended that the volume rates of application are kept to *minimum* practical levels appropriate to the development of the plant canopy.

### 3.2 Metconazole/wheat, powdery mildew

Application of the metconazole DCII formulation to wheat plants gave only slight indications of control of one-day-old infections of powdery mildew at the highest application rate (50 g AI $ha^{-1}$) tested in two trials in this study (Table 4), which was in agreement with previous studies.[2] Change of the volume rate of application between 150 and 500 litre $ha^{-1}$ had little effect on this poor performance in both trials.

However, the adjuvant, 'Dobanol' 91-6 gave substantial and systematic improvements to the performance of DCII with increase of adjuvant application rate from 125 to 500 g $ha^{-1}$, in complete agreement with previous results.[2] Increase of volume rates of application with these DCII/adjuvant combinations gave no systematic, and usually statistically insignificant, changes in performance (Table 4). This was in contrast to the previous *decreases* in performance brought about by higher volume rates with the WPI dimethomorph formulations with an adjuvant on potatoes.

Explanations for these fungicidal activity patterns and observations were first sought from measurement of the spray depositions on both wheat plants and watchglasses, placed on pots amongst the plants, during spray application.

At 150 litre $ha^{-1}$, deposition of spray solution without formulation or 'Dobanol' 91-6, i.e. water, on watchglasses (1·7 $\mu l\ cm^{-2}$) was slightly higher than the intended nominal value (1·5 $\mu l\ cm^{-2}$) and this remained essentially unchanged up to a 'Dobanol' 91-6 application rate of 500 g $ha^{-1}$ (Table 5). Addition of DCII to these solutions, however, caused a marked reduction in spray deposition to between 1·3 and 1·1 $\mu l\ cm^{-2}$, depending on 'Dobanol' 91-6 concentration. This effect was repeated at the application volume rates of 300 and 500 litre $ha^{-1}$. An explanation for this effect can be found from examination of the spray patterns produced by the various solutions through the 80015 nozzle operating at the pressure (117 kPa) used for the spray trials. Addition of 'Dobanol' 91-6 (125 g $ha^{-1}$) to water actually increased the triangulation of the spray swath

**TABLE 4**
Effect of Volume Rate of Application on the Performance of DCII/'Dobanol' 91-6 Combinations in Controlling Powdery Mildew on Wheat

| *Nominal application volume rate (litre $ha^{-1}$)* | *'Dobanol' 91–6 application rate (g $ha^{-1}$)* | *Infection score*[a] *DCH application rate (g AI $ha^{-1}$)* 6.3 | 12.5 | 25 | 50 | *$ED_{90}$ (g AI $ha^{-1}$)* *Calculated value*[b] | *95% Confidence limits* |
|---|---|---|---|---|---|---|---|
| 150 | 0 | 8·6 | 8·6 | 8·3 | 7·0 | 563a | 244<br>1300 |
| | 125 | 8·0 | 7·6 | 6·0 | 2·8 | 160ab | 91<br>281 |
| | 500 | 6·5 | 3·9 | 2·0 | 1·6 | 54c | 35<br>84 |
| 300 | 0 | 8·9 | 8·0 | 8·0 | 5·3 | 338a | 176<br>652 |
| | 125 | 8·4 | 6·0 | 6·9 | 4·5 | 243a | 143<br>412 |
| | 500 | 7·5 | 4·8 | 3·3 | 1·8 | 79bc | 51<br>124 |
| 500 | 0 | 8·6 | 7·9 | 8·1 | 6·6 | 493a | 245<br>993 |
| | 125 | 8·1 | 7·3 | 6·3 | 4·0 | 202ab | 115<br>353 |
| | 500 | 8·1 | 5·8 | 3·4 | 1·4 | 82bc | 56<br>121 |

[a] Scale 0–9; 0 = no infection, 9 = complete infection. Infection score on water-sprayed control plants = 9·0.
[b] $ED_{90}$ values with the same letter are not significantly different at a 95% confidence level.

**TABLE 5**
Effects of Spray Volume Rate and DCII and 'Dobanol' 91-6 Application Rates on Spray Deposition onto Watchglasses and Wheat Leaves

| *Nominal application volume rate (litre ha$^{-1}$)* | *'Dobanol' 91-6 application rate (g ha$^{-1}$)* | *Deposition (µl cm$^{-2}$)* | | | | *Deposition Leaf/watchglass (%)* | |
|---|---|---|---|---|---|---|---|
| | | *Watchglass*[a] | | *Wheat leaf*[b] | | | |
| | | *DCII application rate (g AI ha$^{-1}$)* | | | | | |
| | | *0* | *50* | *0* | *50* | *0* | *50* |
| 150 | 0 | 1·7 | 1·3 | 0·13 | 0·13 | 8 | 10 |
| | 125 | 1·8 | 1·2 | 0·32 | 0·16 | 18 | 13 |
| | 500 | 1·7 | 1·1 | 0·46 | 0·22 | 27 | 20 |
| 300 | 0 | 2·8 | 2·3 | 0·13 | 0·13 | 5 | 6 |
| | 125 | 3·3 | 2·4 | 0·55 | 0·24 | 17 | 10 |
| | 500 | 3·2 | 2·3 | 0·72 | 0·26 | 22 | 12 |
| 500 | 0 | 5·7 | 4·3 | 0·16 | 0·22 | 3 | 5 |
| | 125 | 6·2 | 4·2 | 0·87 | 0·31 | 14 | 7 |
| | 500 | 5·3 | 3·7 | 1·12 | 0·52 | 21 | 14 |

[a] Mean of duplicates.
[b] Mean of four replicates.

(cf. Figs 1(a), 1(b)). Further increase in 'Dobanol' 91-6 concentration, equivalent to 500 g ha$^{-1}$, had little further effect (cf. Figs 1(b), 1(c)). However the volumes deposited in the patternator tubes (L1–L3 and R1–R3), coincident with the positions of the watchglasses (and plants) in the spray trays, remained relatively unchanged (Table 6). On the other hand when DCII was added to water the triangulation almost disappeared (Fig. 2(a)) and this effect dominated that introduced by 'Dobanol' 91-6 (Figs 2(b), 2(c)). The net result was that there was a reduction in volumes deposited in the patternator troughs (84–80%) and on the watchglasses (74–64%) over that achieved by water (Table 6).

These reductions, brought about by the effects of DCII on the spray swath pattern, were approximately followed by the measured depositions on the wheat plants, except that deposition from the spray solution containing only DCII was higher than expected from the decrease in deposition on the watchglasses at all volume rates of application (Table 5). In this case these spray solutions would have possessed a much lower dynamic surface tension than water, owing to the emulsifiers in DCII, and it is believed that this will have increased spray drop capture on a difficult-to-wet surface such as a wheat leaf.[12] There were therefore two opposing effects which governed the observed depositions on the wheat plants for all the matrix of solutions, (a) effect of DCII on the spray pattern which *reduced* deposition at the location of the plants in the spray trays and (b) decrease of dynamic surface tension by either DCII or 'Dobanol' 91-6 which *increased* spray deposition on the difficult-to-wet wheat leaf surfaces.

**TABLE 6**
Comparison of Patternator and Watchglass Depositions for Water and DCII/'Dobanol' 91-6 Combinations at a Nominal Application Volume Rate of 150 litre ha$^{-1}$

| *'Dobanol' 91-6 application rate (g ha$^{-1}$)* | *Deposition relative to water* | | | |
|---|---|---|---|---|
| | *Patternator*[a] | | *Watchglass* | |
| | *Water* | *DCII (50 g AI ha$^{-1}$)* | *Water* | *DCII (50 g AI ha$^{-1}$)* |
| 0 | 1 | 0·84 | 1 | 0·74 |
| 125 | 1·06 | 0·81 | 1·04 | 0·71 |
| 500 | 1·05 | 0·80 | 0·98 | 0·64 |

[a] Taking the mean values for troughs L1–L3 and R1–R3.

The effects of 'Dobanol' 91-6 in increasing spray deposition on the wheat leaves were clearly seen with those solutions containing no DCII, while the results from the combination of the two effects may be more easily seen by inspection of the percentage ratios of the depositions on the leaves and on the watchglasses (Table 5).

The fungicidal performances of these DCII/'Dobanol' 91-6 combinations were, in their turn, a combination of increased deposition *and*, probably, enhanced uptake of metconazole into leaf cellular tissue, both with increase of 'Dobanol' 91-6 application rate. One further point concerning these DCII/'Dobanol' 91-6 combinations was that their depositions on wheat, as a proportion of the spray available for deposition, *declined* with increase of application volume. This effect, on its own, would therefore reduce deposition of metconazole and its fungicidal effectiveness.

The overall conclusion is that, despite the complexity of several interacting factors, variation of the volume rate of application of DCII/'Dobanol' 91-6 combinations onto wheat plants is likely to have only a small influence on their fungicidal performance. For field trials purposes, therefore, this would be unlikely to be a crucial factor and any volume rate of application up to 500 litre $ha^{-1}$ could be adopted that would be appropriate to the crop growth stage/canopy development.

### 3.3 Flamprop-M-isopropyl/oats

Application of the flamprop-M-isopropyl ECIII formulation resulted in some activity ($ED_{90}$ 777 g AI $ha^{-1}$ at 150 litre $ha^{-1}$) in reducing the growth of the second leaf (Table 7). As observed previously,[2] this activity can be significantly increased by the addition of 'Dobanol' 25-7 (250 g $ha^{-1}$ and 1000 g $ha^{-1}$) to give $ED_{90}$ values of 238 and 179 g AI $ha^{-1}$ respectively at a volume application rate of 150 litre $ha^{-1}$ (Table 7). However, what was not known previously is that this enhancement in performance could be further improved by *increasing* the spray volume rate of application, such that a 500 litre $ha^{-1}$ the $ED_{90}$ values for the treatment without 'Dobanol' 25-7 and those with it at 250 and 1000 g $ha^{-1}$ were reduced to 478, 132 and 108 g AI $ha^{-1}$ respectively. This result was not expected and the trial was repeated with similar results (not included). The origins of this better performance at higher volume rates was likely to have resided either in effects on spray

**TABLE 7**
Effect of Volume Rate of Application on the Performance of ECIII/'Dobanol' 25-7 Combinations in Controlling the Growth of Oat Plants

| *Nominal application volume rate (litre $ha^{-1}$)* | *'Dobanol' 25-7 application rate (g $ha^{-1}$)* | *Mean leaf length[a] (mm)* | | | | | *$ED_{90}$ (g AI $ha^{-1}$)* | |
|---|---|---|---|---|---|---|---|---|
| | | *EC III application rate (g AI $ha^{-1}$)* | | | | | *Calculated value[b]* | *95% Confidence limits* |
| | | *38* | *75* | *150* | *300* | *600* | | |
| 150 | 0 | 252 | 239 | 181 | 98 | 88 | 777a | 625<br>967 |
| | 250 | 171 | 154 | 81 | 48 | 55 | 238c | 196<br>290 |
| | 1000 | 165 | 117 | 60 | 47 | 38 | 179c | 154<br>207 |
| 300 | 0 | 247 | 210 | 138 | 84 | 64 | 520b | 435<br>622 |
| | 250 | 145 | 108 | 61 | 47 | 38 | 149cd | 126<br>177 |
| | 1000 | 125 | 80 | 76 | 42 | 36 | 113d | 98<br>130 |
| 500 | 0 | 264 | 229 | 123 | 81 | 47 | 478b | 398<br>574 |
| | 250 | 143 | 85 | 55 | 38 | 38 | 132cd | 111<br>156 |
| | 1000 | 124 | 80 | 47 | 46 | 35 | 108d | 93<br>125 |

[a] Mean length of second leaf: 18-fold replicates; mean leaf length for plants sprayed only with water = 264 mm.
[b] $ED_{90}$ values with the same letter are not significantly different at a 95% confidence level.

deposition or on the subsequent uptake of flamprop-M-isopropyl into plant tissue.

Examination of spray deposition was undertaken. As with 'Dobanol' 91-6 in the metconazole study above, 'Dobanol' 25-7 was likely to have increased the triangulation of the swath pattern (see Figs 1(a)–(c)), but this did not affect the amounts of spray falling on those sections of the spray tray which held the plants and watchglasses, with similar depositions being observed on the watchglasses for water and 'Dobanol' 25-7 at application rates of 250 and 1000 g $ha^{-1}$, at each volume rate (Table 8). However, as with DCII, addition of ECIII may have reduced this triangulation and reduced the amount of spray falling in that section of the spray swath intercepted by the watchglasses (and plants) because, overall, there was a mean reduction in deposition on watchglasses to ~73% of that with solutions containing no formulation, and that observation applied to all volume rates (Table 8). Despite this reduction in the amount of spray available for interception by the oat plants, as with metconazole on wheat, it was observed that the amounts of spray caught by the oat leaves, for the spray solutions containing no 'Dobanol' 25-7 and the largest amount of ECIII, actually increased by ~1·3 to 1·8 times that caught using only water, depending on volume application rate. That increase was attributed to a decrease in dynamic surface tension of the spray solution and more effective capture on the difficult-to-wet oat leaves.[12] Generally these amounts increased further with the co-application of 'Dobanol' 25-7 at each volume rate of application, but it was noticeable that the percentage deposition of available spray *declined* from around 7–8% to 6–7% and then to 4% with increase of volume rate of application from 150 to 300 and to 500 litre $ha^{-1}$ respectively. In other words, there was no evidence that, as the volume rate of application increased, a greater *proportion* of the spray, and hence flamprop-M-isopropyl, was deposited on the oat leaves. In fact the contrary occurred, as was observed for the DCII/'Dobanol' 91-6/wheat situation (see percentage depositions in Tables 8 and 5). The reason for this less efficient capture at higher volume rates is unknown. Clearly there are several different and opposing effects operating on the spray deposition/retention process.

The conclusion was that an increase in the amount of CPA captured with increase of spray volume could not account for the improvement of biological performance, and it must have been that the uptake of flamprop-M-isopropyl into plant tissue was aided both by 'Dobanol' 25-7 and application at higher volume rates of solutions, possibly by better distribution of the spray droplets to more sensitive parts of the oat plants. Coupland, Taylor and Caseley[18] found that application of benzoylprop-ethyl, an analogue of flamprop-M-isopropyl with the same mode of action in the meristem of oat, to the lamina base of the first leaf of oat was the only treatment which resulted in activity in their test. They speculated that this could have been a result of (a) placing the compound nearer to its site of action, (b) of having a longer drying period for the droplets in the more humid regions at the base of the plant and (c) easier penetration across the less waxy and well-developed cuticle on the interior surfaces of the basal regions. It could be that the higher volume rates of application in this study resulted in a greater amount of

**TABLE 8**
Effects of Spray Volume Rate, ECIII and 'Dobanol' 25-7 Application Rates on Spray Deposition on Watchglasses and Oat Leaves

| | | *Deposition (μl $cm^{-2}$)* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *Watchglass*[a] | | | *Oat leaf*[b] | | | *Deposition Leaf/watchglass (%)* | | |
| | | *ECIII application rate (g AI $ha^{-1}$)* | | | | | | | | |
| *Nominal application volume rate (litre $ha^{-1}$)* | *'Dobanol' 25-7 application rate (g $ha^{-1}$)* | *0* | *150* | *600* | *0* | *150* | *600* | *0* | *150* | *600* |
| 150 | 0 | 1·8 | 1·2 | 1·4 | 0·05 | 0·03 | 0·09 | 3 | 3 | 6 |
| | 250 | 1·8 | 1·4 | 1·4 | 0·11 | 0·05 | 0·11 | 6 | 4 | 8 |
| | 1000 | 1·8 | 1·2 | 1·3 | 0·12 | 0·07 | 0·09 | 7 | 6 | 7 |
| 300 | 0 | 3·4 | 2·3 | 2·4 | 0·06 | 0·05 | 0·08 | 2 | 2 | 3 |
| | 250 | 3·3 | 2·4 | 2·1 | 0·24 | 0·11 | 0·12 | 7 | 5 | 6 |
| | 1000 | 3·2 | 2·3 | 2·5 | 0·25 | 0·13 | 0·17 | 8 | 6 | 7 |
| 500 | 0 | 5·5 | 4·1 | 3·9 | 0·09 | 0·09 | 0·12 | 2 | 2 | 3 |
| | 250 | 5·5 | 4·1 | 4·0 | 0·40 | 0·15 | 0·15 | 7 | 4 | 4 |
| | 1000 | 5·6 | 4·0 | 4·1 | 0·42 | 0·14 | 0·18 | 8 | 4 | 4 |

[a] Mean of duplicates.
[b] Mean of seven replicates.

the spray eventually residing in the basal regions of the oat plants. This point could be resolved by a more detailed study of the distribution of the spray deposits with change in volume rate and a study of the uptake of flamprop-M-isopropyl through the upper and lower part of the first leaf of the oat plants using $^{14}C$-labelled compound.

One final point concerning the spray depositions is that deposition on oat plants at the first-leaf stage was even more difficult than that on wheat plants at a similar growth stage. The observed deposition of water on oat leaves was only 3% of that on watchglasses (Table 8) compared with 8% by wheat leaves (Table 5). This general situation may also hold for those spray solutions containing formulation/adjuvant combinations, because the maximum depositions observed on oat were only ~8% of the spray (Table 8) compared with 20–25% on wheat (Table 5), albeit with different spray solutions, and probably related to a difference in the capture efficiency and/or morphology of the two types of plant,[11,12,19] even though they appear similar.

## 4 CONCLUSIONS

It has been shown that variation of the volume rate of application, by altering track speed only, can change the biological performance of products, including those containing spray tank adjuvants, in one of three ways. On a crop with easily wet leaves, such as potato, increase of volume rate of application of formulation/adjuvant combinations decreased performance by promoting spray drop coalescence and run-off, the adjuvant involved being one that would otherwise increase performance, presumably by enhancing foliar uptake of the active ingredient. On crops with difficult-to-wet leaf surfaces, such as wheat and oat, increase of volume rate either had no effect (wheat) or increased performance (oat). These observations were attributed to an interaction of opposing factors which affected spray patterns, spray deposition and foliar penetration, the proportions of which differed between the two cases.

In the transfer of formulations, particularly those containing relatively high amounts of surfactant adjuvants either in the formulation or as spray tank additions, from glasshouse to field situations it is important to understand the impact of variables, such as volume rate of application, on the performance of those formulations. Such information may be used to guide the design of field trials and aid interpretation of field results evaluating adjuvant-enhanced CPA performances.

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